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The Technology of the National Ignition Facility

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The National Ignition Facility (NIF), currently under construction at the University of California's Lawrence Livermore National Laboratory is a 192-beam, 1.8-Megajoule, 500-Terawat, 351-nm laser for inertial confinement fusion and high energy density experimental studies. NIF is being built by the Department of Energy and the National Nuclear Security Agency to provide an experimental test bed for the U.S. Stockpile Stewardship Program to ensure the country's nuclear deterrent without underground nuclear testing. A number of significant technology breakthroughs have been achieved in the course of designing NIF. This presentation will discuss some of the technology challenges and solutions that have made NIF possible.

1. Introduction

The National Ignition Facility (NIF) currently under construction at the Lawrence Livermore National Laboratory (LLNL) will be a U. S. Department of Energy and National Nuclear Security Administration (NNSA) national center to study inertial confinement fusion and the physics of extreme energy densities and pressures. It will be a vital element of the NNSA Stockpile Stewardship Program (SSP), which ensures the reliability and safety of U. S. nuclear weapons without full scale underground nuclear testing. The SSP will achieve this through a combination of above ground test facilities and powerful computer simulations using the NNSA's Accelerated Scientific Computing Initiative (ASCI). In NIF up to 192 extremely powerful laser beams will compress small fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions.

2. A Description of NIF

The National Ignition Facility is shown schematically in Figure 1. NIF consists of four main elements: a laser system and optical components; the target chamber and its experimental systems; an environmentally controlled building housing the laser system and target area; and an integrated computer control system.

NIF's laser system, the heart of the facility, features 192 high-power laser beams. Together, the laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This can be compared with the energy that was available in the Nova laser, which was operated at LLNL between 1983 and 1999. Nova was configured with 10 laser beams, each of which produced approximately 4.5 kilojoules of energy. Currently the largest operating laser is the Omega Laser at the University of Rochester's Laboratory for Laser Energetics. Omega consists of 60 laser beams delivering a total of 40 kilojoules of energy. Figure 2 shows one of

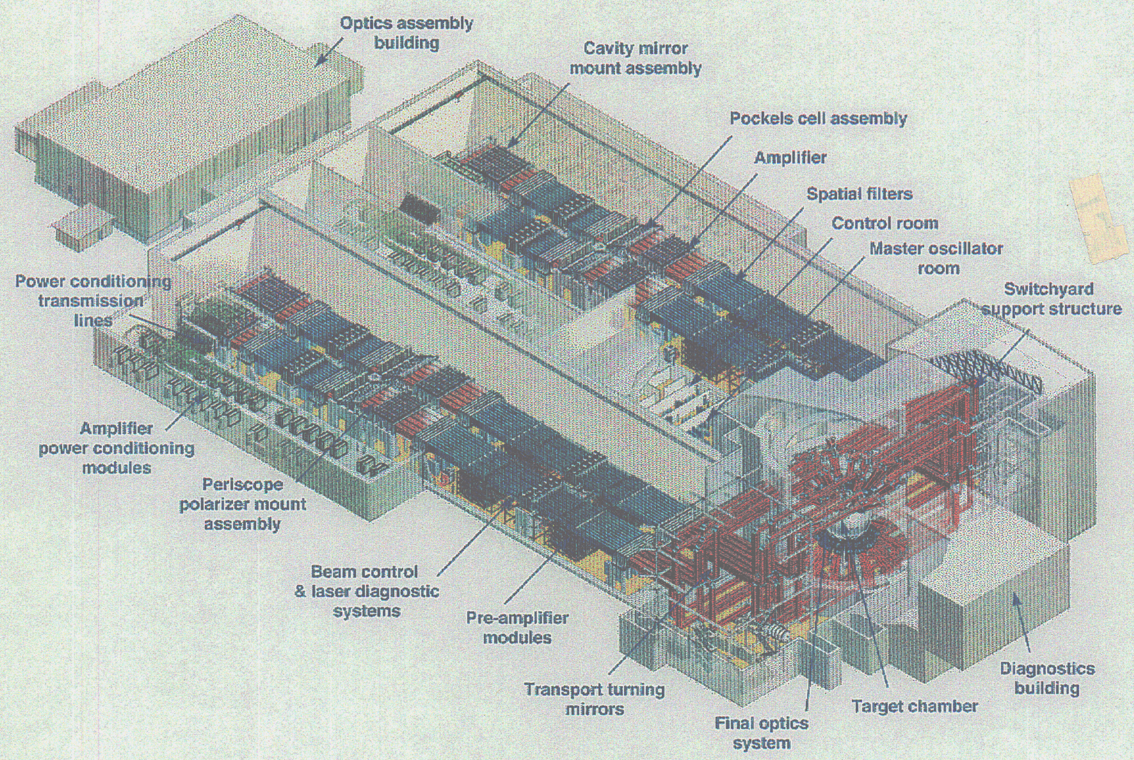

Figure 1. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

the 192 laser beams, detailing the key technologies that make NIF possible. A NIF laser beam begins with a very modest nanojoule energy pulse from the master oscillator, a diode pumped fiber laser system that can provide a variety pulse shape suitable for a wide range of experiments, from ICF implosions to high energy extended pulses for weapons effects experiments. The master oscillator pulse is shaped in time and smoothed in intensity and then transported to preamplifier modules (PAMs) for amplification and beam shaping. Each PAM first amplifies the pulse by a factor of one million (to a millijoule) and then boosts the pulse once again, this time to a maximum of 22 joules, by passing the beam four times through a flashlamp-pumped amplifier. There are total of 48 PAMs on NIF, each feeding a "quad" of four laser beams.

From the PAM the laser beam next enters the main laser system, which consists of two large amplifier units – the power amplifier and the main amplifier. These amplifier systems are designed to efficiently amplify the nominal 1 joule input pulse from the PAM to the required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics. The amplifiers, with 16 glass slabs per beam, are arranged with 11 slabs in the main amplifier section and 5 slabs in the power amplifier section. Together these amplifiers provide 99.9% of NIF's power and energy. The amplifiers use 42 kilogram slabs, 46 cm x 81 cm x 3.4 cm, of neodymium-doped phosphate glass set vertically on edge at Brewster's angle to minimize reflective losses in the laser beam. The slabs are stacked four high and two wide to accommodate a "bundle" of eight laser beams (Figure 3).

The slabs are surrounded by vertical arrays of flashlamps, measuring 180 cm in length. 7600 flashlamps and 3072 glass slabs are required for NIF's 192 laser beams. Each flashlamp is driven by 30,000 joules of electrical energy. The intense white light from the flashlamps

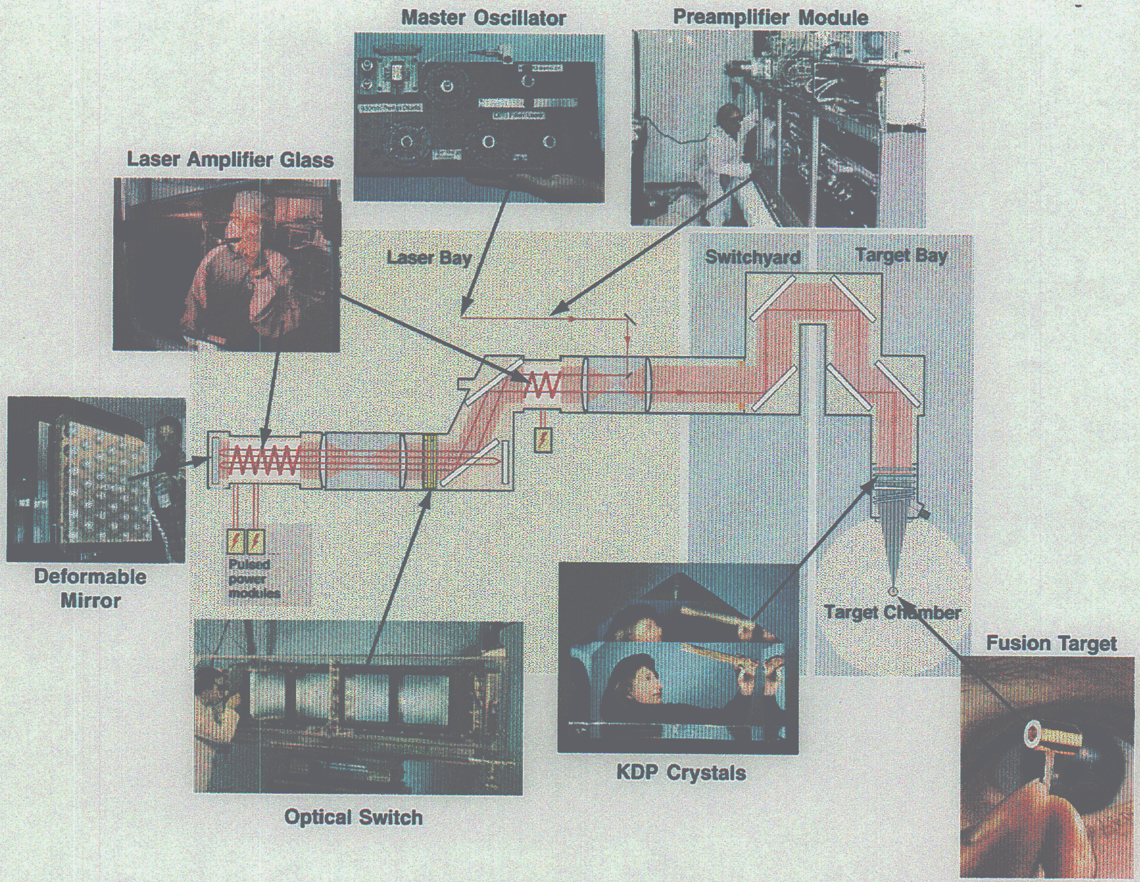

Figure 2. Schematic representation of a NIF laser beam line highlighting some of the key technology developments.

excites the neodymium in the laser slabs to provide optical gain at the primary infrared wavelength of the laser. Some of the energy stored in the neodymium is released when the laser beam passes through the slab. Advances in glass amplifier technology allow NIF to operate with less than twice the number of flashlamps than Nova even though the laser system will produce 60 times more output energy. The flashlamps will be cooled between shots along with the amplifier slabs using nitrogen gas. NIF will be able to shoot once every 8 hours and a shot rate enhancement program funded by our collaborators from the United Kingdom is working to increase the shot rate so that NIF can be fired once every four hours.

The NIF amplifiers receive their power from the Power Conditioning System (PCS), which consists of the highest energy array of electrical capacitors ever assembled. The system's design is a collaboration among Sandia National Laboratories in Albuquerque, LLNL, and industry. The PCS will occupy four capacitor bays (shown in Figure 1) adjacent to each laser bay. Each PCS module is configured with eight, 20-capacitor modules delivering 1.7 megajoules per module that power the flashlamps for one beam. The system must deliver over 300 million joules of electrical energy to the flashlamp assemblies in each laser beam. The NIF PCS delivers electrical energy nearly 10 times cheaper per joule than on Nova. Recent tests on a prototype PCS and flashlamp system have now fired over 3000 times at a rate of 1200 shots per month.

A key component in the laser chain is a kind of optical switch called a plasma electrode Pockels cell (PEPC), which allows the beam to pass four times through the main amplifier cavity. This device uses electrically induced changes in the refractive index of an electro-optic

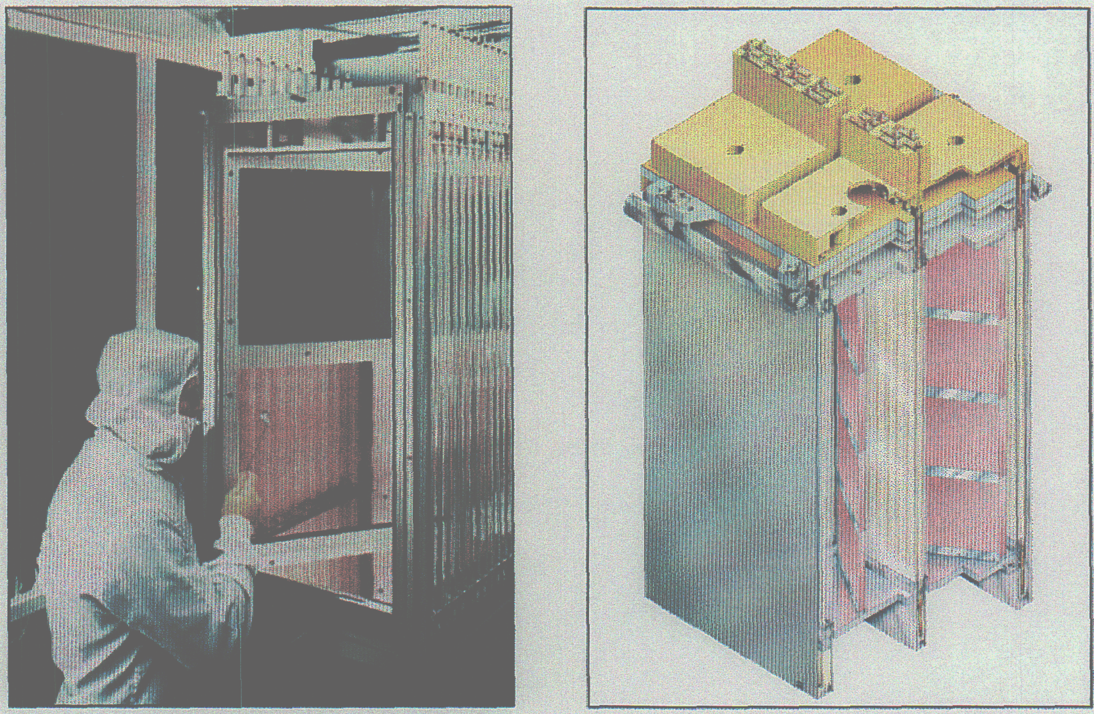

Figure 3. The photograph on the left shows an amplifier used on Beamlet, the scientific prototype of NIF. The illustration on the right shows the NIF 2 x 4 amplifier in cutaway view.

crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the PEPC allows light to pass through or reflect off the polarizer. The PEPC will essentially trap the laser light between two mirrors as it makes four one-way passes through the main amplifier system before being switched out to continue its way to the target chamber. The PEPC consists of thin KDP plates sandwiched between tow gas-discharge plasmas that are so tenuous they have no effect on the laser beam passing through the cell. Nonetheless, the plasmas serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently. Figure 2 shows a prototype 4-cell PEPC (optical switch) that will be stacked vertically in a single unit called a line-replaceable unit.

There are many other parts of NIF that are not covered in detail here. All major laser components are assembled in clean modules called line-replaceable units or LRUs. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filters assemblies. All LRUs are designed to be assembled and installed into NIF's beampath infrastructure system, the exoskeleton of NIF, while maintaining a high level of cleanliness required for proper laser operation. Our industrial partner, Jacobs Facilities, Inc. is responsible for the installation, integration, and commissioning of the NIF laser beampath infrastructure, which will ensure that the laser maintains the required cleanliness levels throughout the installation and commissioning phase of the Project.

The NIF target area consists of the 10-meter diameter high-vacuum target chamber shown in Figure 4. The target chamber contains a large number of laser entry ports as well as over 100 ports for diagnostic instrumentation and target insertion. Each port allows a quad of 4 laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing beam smoothing gratings,

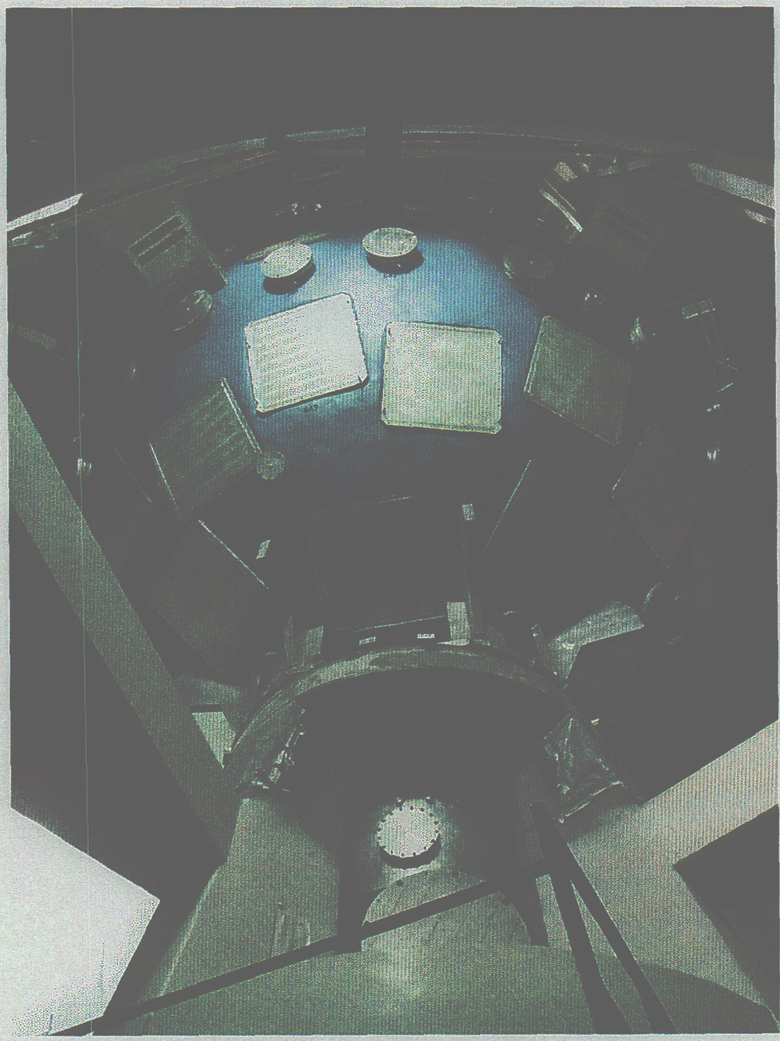

Figure 4. NIF's 10-meter diameter target chamber mounted in the target bay and viewed from below.

additional KDP and deuterated KDP plates for second and third harmonic generation to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam. The NIF target chamber and final focusing system has been designed with maximum flexibility for experimental users. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs half the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to indirectly implode the capsule. NIF can also be configured in a "direct drive" arrangement of beams, by moving some quads of beams from the upper and lower hemispheres into a more symmetric arrangement of beams. Direct drive ignition requires better energy and power balance between laser beams and better beam smoothing and focusing but the simpler geometry makes direct drive inertial confinement fusion more attractive for ultimately producing a viable power production plant.

Figure 5. Aerial photograph of the NIF site at Lawrence Livermore National Laboratory taken in April 2001.

3. NIF Project Status

NIF is currently four years into its construction. Figure 5 shows a recent aerial photograph of the NIF site. The conventional building construction is nearly complete. The 8,000 square foot class-100 clean room Optics Assembly Building is undergoing commissioning of LRU assembly, handling and transport equipment. Both large laser bays are operating under class-100,000 clean room protocols. Over 1500 tons of beampath infrastructure have now been installed in the laser bays. The NIF Project is now entering the installation and commissioning phase over the next few years. First light, which is defined as the first quad of four laser beams focused to target chamber center is scheduled for June 2004. Full completion of all 192 laser beams is scheduled for September 2008. In the time between first light and project completion, approximately 1500 experiments in support of the SSP, inertial confinement fusion, high- energy-density physics, weapons effects, inertial fusion energy, and basic science will have been performed.

After project completion, NIF is expected to provide approximately 750 shots per year for a wide variety of experimental users. Recently NIF was designated as a National User Facility with the support of the NNSA Office of Defense Programs. A National User Support Organization is now being put in place to provide the necessary interface between the user communities and the national NIF Program. The first Director of NIF is Dr. George H. Miller, from LLNL, who also serves as the Associated Director for NIF Programs at LLNL.

4. Conclusions

The National Ignition Facility has come a long way since the first DOE critical decision in January 1993 affirmed the need for NIF and authorized the conceptual design process. In that time NIF has met every scientific and technical challenge and is now in the final stages of design and construction prior to commencing installation of the 192 laser beams. By 2004 this unique facility will be providing the first glimpses of conditions heretofore only found in the most extreme environments imaginable under repeatable and well-characterized laboratory conditions for the benefit of national security and science.

Acknowledgements

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References

For more information on the NIF Project please visit our web site at http://www.llnl.gov/nif